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New technology on seismic reinforcement of pile foundation for long life bridges

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Abstract

Nowadays, based on the experiences in the recent severe earthquakes, a certain level of seismic performance is required for the foundation design of newly-built bridges. Moreover, there are so many existing pile foundations with serious deteriorations and damages. In this report, new technique to improve seismic performance of pile foundation, in which ground improvement is provided around the existing piles in very soft or liquefiable soil, is proposed. It enables existing bridges to be sustainable and long life structures. The patent to this technique named the Composite-Pile Method has been granted in Japan in 2012. Strength and deformation of improved soil test pieces having different levels of strength were fully investigated through various types of material tests. Seismic performance of pile foundation with improved soil subjected to Level 2 Earthquake wave was then verified by large-scale shaking table tests for model piles. The bending strain in the existing piles surrounded by improved soil with a uni-axial strength of greater than 300kN/m², when subjected to severe earthquake, was reduced by half of the strain generated in the piles without soil improvement, which leads to the reduction of response displacement of the piles. It was clarified that, based on the test results, seismic performance of pile foundation could be drastically improved by the proposed method. Practical application of the proposed method, when needed in the future, will be undertaken for higher safety of public structures.

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1. Introduction

Recently, major earthquakes have occurred frequently around the world, including in Japan. Therefore, design methods for new bridges are required to achieve a certain level of seismic performance, based on the lesson of previous disasters caused by Level 2 ground motions from inland and inter-plate earthquakes [1]. Many bridges in Japan constructed during the period of high economic growth 40 ~ 50 years ago have been seriously deteriorated and damaged. As a countermeasure, and an important national policy, seismic reinforcement for the superstructure and the substructure of existing bridges has been performed based on their conditions. Seismic reinforcement to existing bridge foundations, however, have not been conducted due to the lack of understanding of seismic performance of existing bridge foundations and development of rational construction methods for strengthening the seismic resistance of existing bridge foundations. In light of the above, we have developed a seismic reinforcement method for existing pile foundation named as the composite pile method [2]. In this new method, surrounding ground of the existing pile foundation is replaced with improved soil columns. The main purpose of this method is to improve sub grade reaction at pile head, and increase the seismic resistance of the pile foundation during earthquake; this differs from methods that integrate reinforcing materials into the existing foundation. In this construction method, the construction costs are lower and the workability is superior to those of conventional construction methods. Peat ground and liquefiable ground are typical soft grounds. Pile foundations in such soft grounds usually pose large lateral displacement at pile heads during earthquake due to the weakness of sub grade reaction to the piles. In this study, the needs for seismic reinforcement to existing pile foundations constructed in such soft grounds and the technologies for diagnosing the aseismic capacity of existing pile foundations was examined. The engineering feasibility of the composite pile method for existing pile foundations was verified through large scale shaking table experiments under strong seismic motion. The validity of the proposed method was discussed on the basis of the test results. This paper introduces the detail test program and findings.

2. An aseismic reinforcement method for existing pile foundations

2.1. Needs for seismic reinforcement

The highway network in Japan involves about 700,000 bridges, and many of them have remarkably poor seismic resistance, as they have been in service for 40 to 50 years. Therefore, measures are sought to maintain these great assets under severe financial constraints, and the seismic reinforcement of piers and installation of collapse-prevention devices for existing bridges have been conducted in advance. In some bridges with serious damage or deterioration, reconstruction were considered and performed. In the case of building new bridge foundations, a certain degree of plastic deformation is allowed for large-scale seismic load equivalent to Level 2 earthquake motions. In existing bridges, foundation failure is rare before the substructure fails, and a survey revealed that installing dampers or adjusting passive earth pressure eliminates the need for seismic reinforcement for many bridge foundations. However, the 2011 Off the Pacific Coast of Tohoku Earthquake caused damage to existing concrete piles and caisson pile caps installed in soft ground that caused the highways out of service for a long time. For that reason, the development of an evaluation method for the seismic performance of existing bridge foundations and the reconsideration of required seismic performance according to the relative importance of structures are required in highway bridge construction [3]. There are argues that earthquake damage to the pile foundations does not cause the bridge to collapse. However, bridge pier reinforcement works and collapse-prevention devices are designed on the premise that the pile foundation satisfies a certain horizontal load bearing capacity. In the event that the foundation receives unexpectedly large deformation during a strong earthquake, there is the possibility that the pier will receive extra-large displacement, shear collapse will occur and the bridge collapse-prevention devices will fracture. If the collapse-prevention devices of the bridge behave unnaturally, the foundation will accept the entire seismic load and, in the worst case, the existing pile foundations will collapse.

For the following three reasons, necessary seismic reinforcement of existing pile foundations has to be studied.

- After revising the seismic design codes, higher seismic capacity comparing with the current codes has been required for the newly constructed bridge pile foundations [1].
- The top part of a bridge is heavy; therefore, even if the stiffness of the superstructure and the substructure are improved, in some bridge cases built on soft ground and liquefiable ground, the total seismic capacity of the bridge cannot be improved.
- When a pier is reinforced by winding with steel plates, the additional load will act on the existing pile foundation, and it might lead to failure of foundations before the failure of other parts during earthquake.

2.2. Method of seismic safety evaluation

The needs of seismic reinforcement for existing pile foundations should be determined according to the current seismic design method and the required seismic capacity of the structure. In local governments, however, not even seismic safety evaluation is done appropriately, so proactive measures to achieve the establishment of a disaster-resilient country are demanded. Therefore, in this paper, the diagnostic procedure for seismic reinforcement of existing pile foundations is proposed as a reference for local authorities [4]. The diagnostic procedure for seismic reinforcement is only briefly addressed in this paper. The purpose of this diagnostic procedure for seismic reinforcement is to determine the need for reinforcement by verification of the seismic performance of existing pile foundations. Specifically, in the case of ultimate lateral strength verification for seismic motion of Level 1 and 2, it is necessary to consider the yield resistance of materials and also to consider reinforcement of the superstructure and substructure. From the results of seismic safety evaluation, if there is a possibility of occurrence of the failure of foundations prior to that of the superstructure or substructure, the implementation of reinforcement will be discussed with relevant management sections. In this procedure, it is important to check geological surveys for liquefaction evaluations, and to confirm whether there is any actual degradation and deformation in the pile foundation. Seismic safety evaluations show that in the cases of deformed pile foundations with remarkably low seismic resistance or pile bent foundations with insufficient seismic capacity, pile foundation reinforcement by large-scale repair in together with substructure reinforcement should be implemented. Also, a comparison of the cost for rebuilding the bridge versus the cost for repairs with reinforcement is required. The main purpose of the seismic safety evaluation for existing pile foundations is to propose a common understanding of the needs for a proper seismic safety evaluation method, rather than to force the implementation of reinforcement.

3. The composite pile method

For seismic reinforcement of existing pile foundations, two points mentioned below should be studied first, assuming a lower seismic capacity than that in current seismic design codes [1].

- The remarkably low strength of pile foundations and their low rigidity (wood piles or RC beams with less rigidity, etc.)
- The occurrence of lateral spreading associated with ground liquefaction.

The basic approach of seismic reinforcement technology for existing pile foundations is roughly divided into following three types [5].

(a) Reinforcing the strength of pile foundations

In one method, the strength of existing pile foundations is increased by the adding new structural members; in another method, the shear strength of the surrounding soil of the pile foundation is increased through ground improvement.

(b) Transmitting earthquake load to good-quality ground

This method is to confirm that existing pile foundations are embedded in the supporting layer, and seismic reinforcement will be done if necessary.

(c) Preventing shear strength degradation caused by liquefaction of the soil around the foundation

Representative seismic reinforcement technologies for existing pile foundations consist of footing reinforcement, additional piles, additional diaphragm walls, additional steel pipe sheet piles, additional caissons, crushed stone columns and ground solidification. However, many of the proposed reinforcement technologies integrate existing pile foundation and reinforcing materials, and no clear verification method for design has been systematized because of the complicated behavior of such a composite structure. Therefore, R&D on a new technology for seismic reinforcement has carried out. In this technology, the seismic resistance of existing pile foundation was increased by deploying ground improvement around pile foundation constructed in soft ground and liquefiable ground as shown in Fig. 1. In this new technology, ground around the existing pile foundation is filled up with solidification-improving materials in peaty soft/liquefaction-prone ground. The peaty soft ground and liquefaction-prone ground have the remarkably low shear strength that characterizes soft ground (Fig. 1). This reinforcement method is tentatively named as the composite pile method. The composite pile method is different from conventional methods that integrate existing pile foundations and reinforcement materials. It improves the ground around existing pile foundations, which means that it is a technology for securing aseismic capacity from possible energy absorption of earthquake motion by strengthening the reaction force of the improved ground. As shown in Fig. 1, in the composite pile method, the range improved by the ground stabilizing material is a 3-D domain formed with the gradient of the surface of passive failure $\theta = (45^\circ + \phi/2)$ (ϕ : angle of shear resistance of soil, it is generally ignored for soft and liquefiable grounds) from the depth of the characteristic length of piles, $1/\beta$ ($\beta = (kD/4E_p I)^{1/4}$), which is the depth of influence of the horizontal resistance of piles on the basis of the limit equilibrium and the Mohr-Coulomb failure criterion.

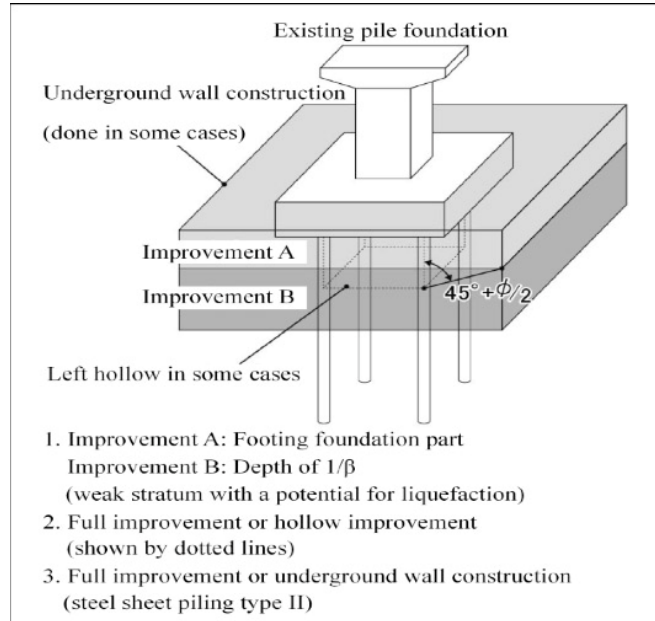


Fig. 1. The composite pile method.

Soil improvement is typically carried out on both the lower part (Improvement B) and from the footing foundation to the upper part (Improvement A). Improving the soil at the footing foundation part is expected to increase the passive earth pressure. In the soil improving work, if the site conditions make it difficult to improve the soil immediately under the footing foundation, the inner side of piles is left non-improvement. Even though the inner side soil of piles under the footing is not improved, the improved ground body around those piles will resist the shear deformation of inner side soil during an earthquake; therefore, it is assumed that excess pore water pressure in the inner side soil of piles is able to be restrained, and potential liquefaction be avoided. In addition, if the improvement area needs to be reduced in size due to the site conditions or if a cofferdam needs to be constructed, underground diaphragm wall (JIS Type II steel sheet piling) is adopted together with the ground improvement.

In the construction methods of soil improvement and steel sheet piling, even where the bridge clearance is low, there are no particular problems with workability, since various machines has developed. It varies with the size of the pile foundation; an around 40% cost-down and 50% time-saving can be achieved with the composite pile method, compared to extension pile method which needs digging and filling. As an example, seismic reinforcement with the extension pile method. In the composite pile method, the strength of the improved body is set according to the required seismic performance of the existing foundation; generally, the unconfined compressive strength is set as $q_u > 300 \text{ kN/m}^2$. And in the seismic design of this composite pile method, following the current seismic design method, seismic performance against earthquake motion of Level 1 is verified with the seismic coefficient method with a spring model of the improved body, and seismic performance against earthquake motion of Level 2 is verified with the ultimate lateral strength method during earthquake and dynamic response analysis or dynamic nonlinear FEM analysis with design base wave motion [6].

4. Result of the large scales shaking experiments

4.1. Experiment outline

Verification of seismic performance of pile foundation with the composite pile method through large-scale shaking experiments is briefly described as follows. A 15-layers laminar box with inner dimensions of L1.2m x W0.8m x H1.0m was loaded on the large-scale shaking table with one shaking direction and served as a model container for the experiments. Four SGP steel pipes with the diameter of 0.0272 m and the wall thickness of 0.0028 m were used to form the group pile foundation. Four typical cases of experiments were carried out. In Case 1, the model ground was formed with three soil layers. The top layer with a thickness of 0.2 m equivalent to the pile characteristics length ($1/\beta$) was untreated peat. The intermediate layer with a thickness of 0.6 m was natural soil. The base layer with a thickness of 0.2 m served as a bearing stratum. In Case 2, the ground model had the same profile as Case 1, and the area of peat top layer around the pile was treated by using ground improvement ($q_u=300 \text{ kN/m}^2$), i.e. composite pile method. The area under the footing remained untreated. As for the range of soil improvement in Case 2, it was determined by using passive failure surface with an angle of $45^\circ + \phi/2$ to the axis of the pile as shown in Fig. 1. In Case 3, the model ground profile was similar with Case 1. Instead of peat soft soil, loose sand with a relative density of $Dr = 40\%$ was used as the top layer. In Case 4, same as Case 2, the top loose sand layer around the pile was treated by using ground improvement ($q_u=300 \text{ kN/m}^2$). Cases 1 and 2 focused on the dynamic performance of pile foundation in peat soft ground, and Case 3 and 4 on the case in liquefiable ground with and without seismic reinforcement by using composite pile method.

4.2. The case of peat soft ground

In the experiments for Cases 1 and 2 with peat soft ground, the input earthquake motion was set at Level 2 interpolate type earthquake. Strong earthquake motion recorded from the 2011 Off the Pacific Coast of Tohoku Earthquake (Type I) for 240 sec was directly input to the base of shaking table (Fig. 2).

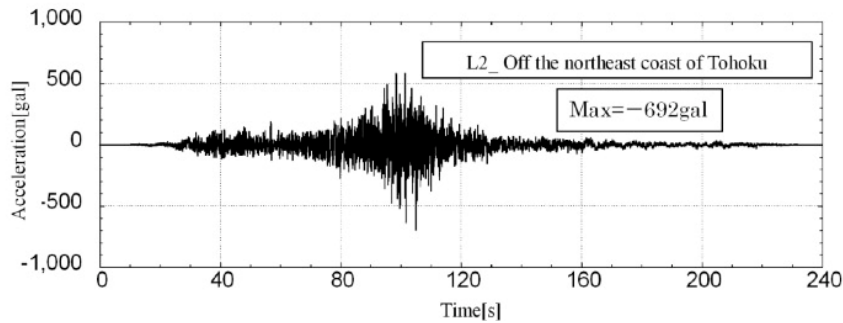


Fig. 2. Input Level 2 earthquake motion for Case 1 and Case 2

The results of shaking experiments for the case of peat soft ground show that the pile head displacement with Level 2 earthquake motion was $y_1 = 81.05$ mm in Case 1 with untreated peat soft ground, and it was $y_2 = 44.78$ mm in Case 2 with composite pile method. The results verified that the pile head displacement was remarkably restrained by using composite pile method. Another shaking experiment was done for the case with ground improvement under footing, no difference in pile head displacement was found comparing with Case 2.

As part of the evaluation of seismic performance with the composite pile method, the occurrence of pile strain was also focused. The strain distribution of each pile for Cases 1 and 2 under Level 2 input earthquake motion is shown in Fig. 3. The figure shows that in Case 1 with untreated peat soft ground, extremely large pile strain $\varepsilon = 4000 \sim 5000 \mu$ occurred at the middle section of pile. In this case, the middle section of the steel pipe pile was fractured and severely deformed after shaking experiment (Fig. 4). However, in Case 2 with the composite pile method, the maximum pile strain was about $\varepsilon = 2000 \mu$ which is half the value of Case 1, and no damage in the improved body was found. Various other experiments on the composite pile method in peat soft ground have also been conducted, and the feasibility of this reinforcement technology for existing pile foundations has been verified.

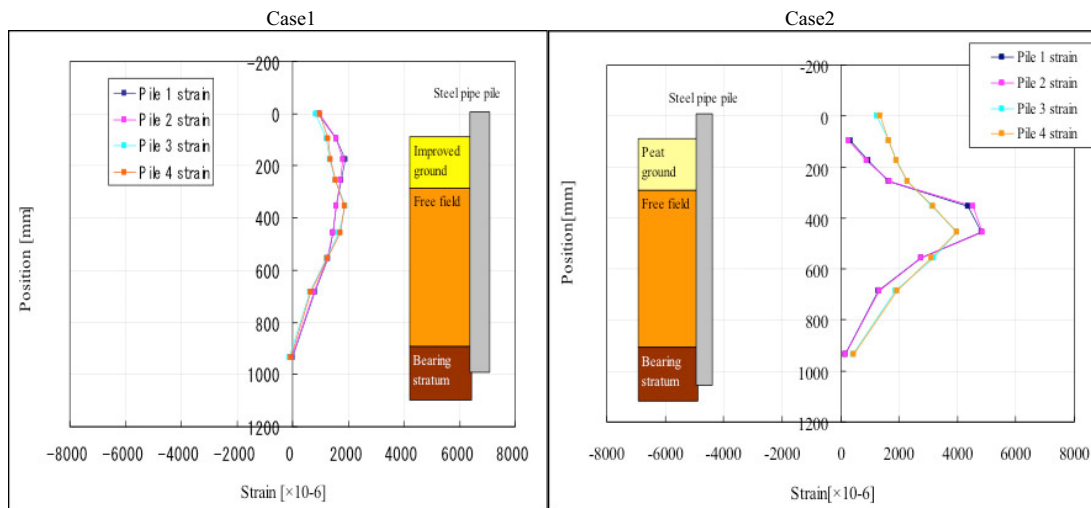


Fig. 3. Strain distribution of each pile under Level 2 earthquake motion.

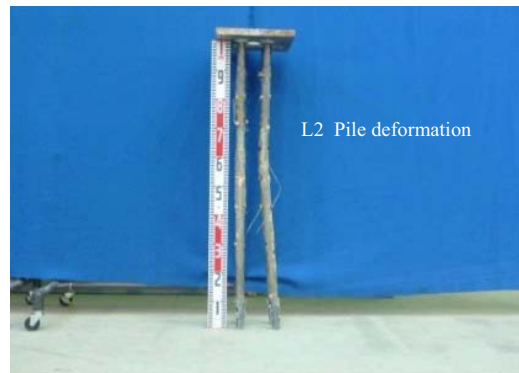


Fig. 4. Pile deformation after shaking experiment (Case 1).

4.3. The case of liquefiable ground

In the shaking experiments Cases 3 and 4 with liquefiable ground, sine waves with the maximum acceleration of 500 gal were used as the input motion from the base of shaking table. The model of Case 3 after shaking with obvious liquefaction on the ground. In Case 4 with composite pile method, although liquefaction occurred in the ground around the improved body, since the displacement of group pile was restrained, no liquefaction under the footing was confirmed from the measurement of excess pore water pressure. In Fig. 4, the comparison of Cases 3 and 4 in seismic pile deformation with sine wave of identical maximum acceleration synchronized with the natural period of the laminar box shows that the maximum seismic deformation with the composite pile method was reduced to about 1/4 ($y_4=5$ mm for Case 4 and $y_3=20$ mm for Case 3).

In Case 4, the improved body was not damaged and declining tendency in the pile strain was found comparing with Case 3. From these results, the seismic reinforcement effect of the composite pile method for existing pile foundations in liquefiable ground was verified.

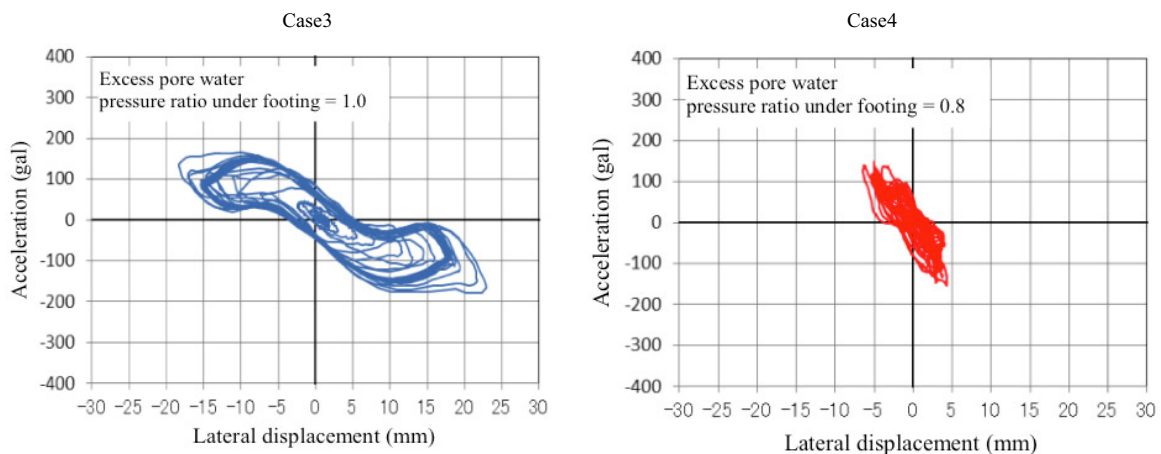


Fig. 5. Response acceleration vs. lateral displacement of the footing for Case 3 and Case 4.

5. Conclusions

The seismic reinforcement methods and their design procedures for existing bridge foundations were reviewed. The engineering feasibility of the composite pile method for existing pile foundations was verified through large-scale shaking table experiments under strong earthquake motion. The validity of this method was discussed on the basis of the experiment results. The findings of this study are summarized as follows.

- As a new technology for the seismic reinforcement of existing pile foundations, the composite pile method has been studied and developed. This method which integrates existing pile foundation and improved ground body is different from other reinforcement methods with additional structural members. The main purpose of this method is to improve the sub grade reaction around existing pile foundations during earthquake.
- The necessity of seismic reinforcement for existing pile foundations has to be identified appropriately according to the current seismic design methods and the necessary seismic capacity. In this paper, the diagnostic procedure for seismic reinforcement of existing pile foundations is briefly introduced. In seismic safety evaluation, ground liquefaction, and damage, degradation and deformation of foundations are the important factors for the safety of pile foundations. As the final stage of diagnosis, the necessity of reinforcement has to be studied mainly through verification of ultimate lateral strength of the pile foundation under Level 1 and 2 earthquake motions, and consultations with related management authorities are also needed.
- The results of shaking experiments in a large-scale shaking table for group pile foundation in peat soft ground under Level 2 inter-plate type earthquake motion show that the maximum lateral displacement of pile foundation with composite pile method is around half of that without composite pile method, and therefore, the effectiveness of composite pile method was verified.
- The results of shaking experiments in a large-scale shaking table for group pile foundation in liquefiable ground under strong earthquake motion show that the maximum lateral displacement of pile foundation with composite pile method is around 1/4 of that without composite pile method, and the increment of excess pore water pressure in the inner part under footing is highly reduced. The feasibility of this method for liquefiable ground is confirmed.

As registered in the NETIS, site management of the composite pile method has already been compiled; and the practical application of this method for existing pile foundation is highly expected.

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